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LINEAR AND NONLINEAR CORRECTIONS IN THE RHIC INTERACTION REGIONS*

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Abstract
A method has been developed to measure operationally the linear and non-linear effects of the interaction region triplets, that gives access to the multipole content through the action kick, by applying closed orbit bumps and analysing tune and orbit shifts. This technique has been extensively tested and used during the RHIC operations in 2001. Measurements were taken at 3 different interaction regions and for different focusing at the interaction point. Non-linear effects up to the dodecapole have been measured as well as the effects of linear, sextupolar and octupolar corrections. An analysis package for the data processing has been developed that through a precise fit of the experimental tune shift data (measured by a phase lock loop technique to better than 10^{-5} resolution) determines the multipole content of an IR triplet.

1 INTRODUCTION

The essence of the interaction region (IR) bumps method to infer local triplet errors from beam data is to measure rms orbit and tune shift as a function of the amplitude of local orbit bumps centered on the IR triplets. The technique itself, together with preliminary results from the RHIC run 2000 and the application to the LHC has been described in [1]. A more detailed discussion of its use for linear correction in the RHIC IR's in run 2000 can be found in [2]. We will report here the progress in testing and using this technique at RHIC during run 2001, that ended in January 2002. The progress on linear correction of the IR's is reported in Section 2. Section 3 is a discussion of the non-linear IR measurement and correction in 2001 while developments and plans for the next RHIC run are the subject of Section 4.

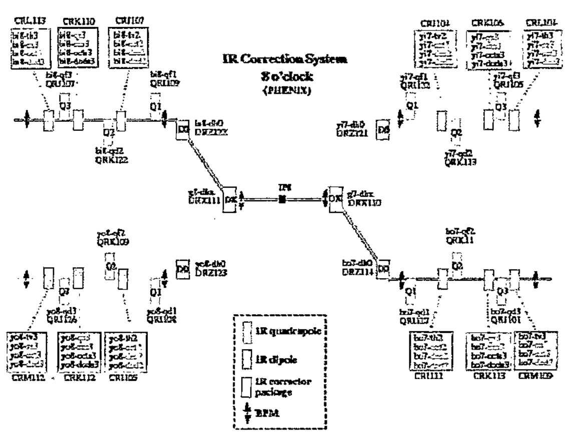

Figure 1. Schematics of the IR correction system in IR8

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RHIC has 6 interaction regions, 4 of which host detectors (IR2, IR6, IR8 and IR10). Local correction packages are located at every IR triplet: all IR skew quadrupole layers (see Section 2) are powered, while power supplies for the non-linear correctors exist only in IR6 and IR8, that are designed for low β^*. Figure 1 is a schematics of the local IR correction system in IR8.

2.LINEAR IR CORRECTION IN RUN 2001

Very early in the 2001 run, we implemented local coupling correction in all RHIC IR's: IP2 IP6 and IP8 skew quadrupole corrector settings are based on data analysis from run 2000 [2], IP4, IP10 and IP12 from 2001 beam data. The 2 methods used to set the correctors (IR bumps and action-phase jump [3]) are in good agreement and the roll in the triplets estimated from beam based IR measurements agree at the 10% level with the alignment roll eventually measured during the shutdown.

Even after local coupling correction there is evidence of residual IR linear errors: differences between the optics model and the measured optics, orbit correction and IR steering bumps not perfectly closed, and large measured vertical dispersion at flattop. So high priority has been placed on better determination of gradient and (residual) coupling errors. For this analysis we used IR bump data collected during dedicated beam experiments time, and orbit data logged during operations. From the IR bump data, the analysis of the rms orbit perturbation outside the IR allows us to determine the gradient error (effect in the same plane as the bump) and the residual coupling error (effect in the plane opposite to the bump). For the analysis of orbit distortions during orbit correction or separation bump removal, a dedicated fitting routine was developed to find the set of gradient/coupling errors that exactly fits the observed orbit errors.

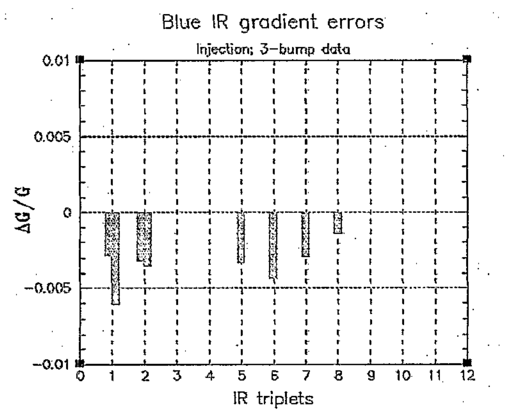

Figure 2. Gradient errors at injection in the Blue ring.

Figure 2 shows the gradient errors at injection in the Blue ring, determined from IR bump data and evidence of a systematic error. Figure 3 shows gradient and residual coupling errors at flattop, from operations data analysis.

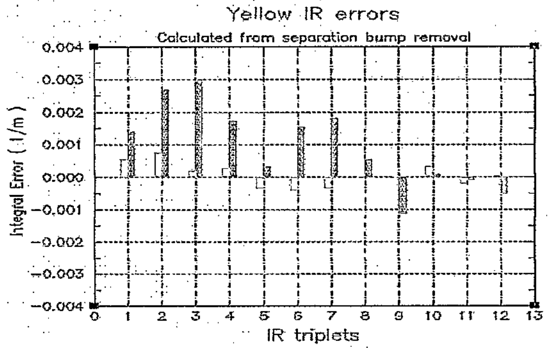

Figure 3. Gradient and residual coupling errors at flattop.

3. NON-LINEAR IR CORRECTION IN RUN 2001

Non-linear IR bump measurements and correction in 2001 focused on IR8, as the run plan was to progressively squeeze the β^* at IP8 to maximize luminosity at the Phenix detector. A complete set of measurements has also been taken at IP2 (Brahms detector) to assess the feasibility of squeezing β^* at IP2 as well. Tune shift versus bump amplitude data taken in run 2001 is listed in Table 1 for different optics configuration.

Table 1. Non-linear IR data summary Run 2001.

Configuration	Optics	Triplets measured
injection	10 m	BO7 YI7 YO5
flattop (Au)	5 m	BO7
flattop (Au)	2 m	BO7 BI8 YI7 YO8 BI1 BO2 YO1 YI2
flattop (Au)	1 m	BO7 BI8 YI7 YO8
flattop (PP)	3 m	YI7 YO8

Two main experimental improvements in 2001 increased respectively the data acquisition speed and data quality. First, the IR local bumps were continuously increased to their maximum amplitude, and data logged in parallel, allowing a full set of triplet data to be taken in a few minutes. Second, we used the PLL (phase lock loop) for tune measurements that can provide better than 10^{-5} resolution. As the latter system was in a commissioning phase, we also used the tune meter and the high frequency Schottky system. During the gold run (Au) beam experiment time dedicated to IR work focused on data taking and non-linear effect calibration and testing. Octupole and sextupole corrections in IR8 were performed during the polarized proton (PP) run.

3.1 Non-linear effects at injection, calibration

A Mathematica analysis package has been developed to analyse experimental IR bump data, that allows the determination of the multipole content of a specific triplet from precise fitting of the tune vs. bump amplitude data. The first priority in run 2001 was to test the capability of this technique for measuring multipoles, first at injection, where the 10m β^* optics allows for larger amplitude (up to 45mm) IR bumps. PLL tune data, corrector currents, and closed orbit were acquired and logged. Data is then processed by the Mathematica package. Pre-processing of raw data is needed to precisely synchronize data from different systems, and to suppress trends (known tune drifts at injection, PLL synchrotron satellite jumping, etc.). The pre-processed data are then fit and the multipoles determined. As an example we discuss the calibration of the method at injection: A local octupole corrector and successively a dodecapole were powered to a known value, and the resulting effect on the beam measured and analysed. Figure 4 shows the amplitude dependent tune for the intentional dodecapole perturbation in IR8, at injection.

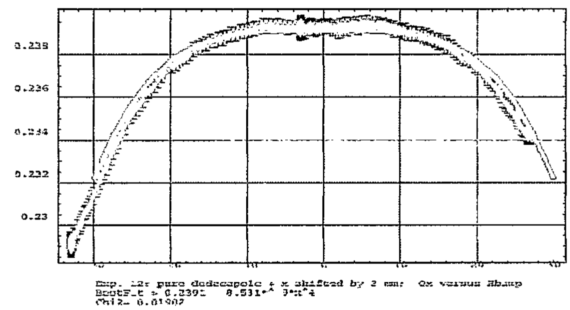

Figure 4. Fit of tune vs. amplitude data for a dodecapole perturbation at injection.

3.2 IR non-linear measurements at flattop

The effect of non-linear IR errors increases with β^{max} in the triplet, hence with smaller β^*. At flattop, during run 2001, β^* was decreased from 5m to 2m in all IR's and to 1m further only in IP8. Indeed, at β^*=1m the effect on the lifetime in the Yellow ring is clear, as can be seen in Figure 5.

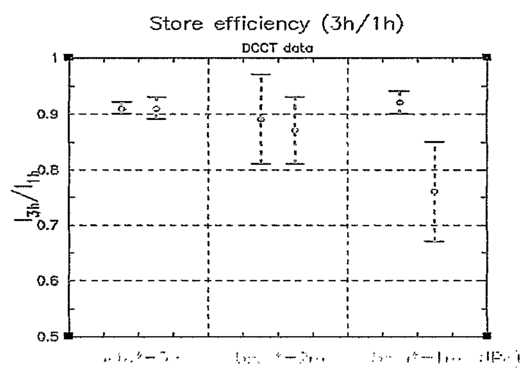

Figure 5. Store efficiency (beam intensity after 3 h over intensity at 1 h) as a function of β^* in IP8.

By comparing IR bump data in the Blue and Yellow IR8 triplets, the tune shift with bump amplitude in Yellow is indeed larger than Blue, supporting the hypothesis that IR errors may contribute to the lifetime problem in Yellow.

Table 2. Tune shift for 5mm bump amplitude in the 7 o'clock Blue and Yellow triplets, at β^*=1m

triplet	bump	ΔQH +5mm	ΔQH -5mm	ΔQV +5mm	ΔQV -5mm
BO7	hor	-0.002	+0.002	0.0006	-0.0008
BO7	ver	-0.0015	+0.001	+0.0004	-0.0001
YI7	hor	+0.0012	-0.001	-0.0025	+0.0045
YI7	ver	+0.0028	-0.003	-0.003	+0.004

3.3 Octupole and sextupole correction at flattop

Interaction region octupole and sextupole corrections were implemented in the Yellow IR8 triplet (YI7 and YO8) during the polarized proton run at flattop (β^*=3m), based on measurements and calibrations taken during gold operations. First, we corrected the octupole effect operationally, by compensating the asymmetry in the tune vs. bump amplitude dependence, with the local octupole correctors, at YI7 first then YO8. Figure 6 shows the PLL horizontal tune measurement during the bump after octupole correction (symmetric dependence).

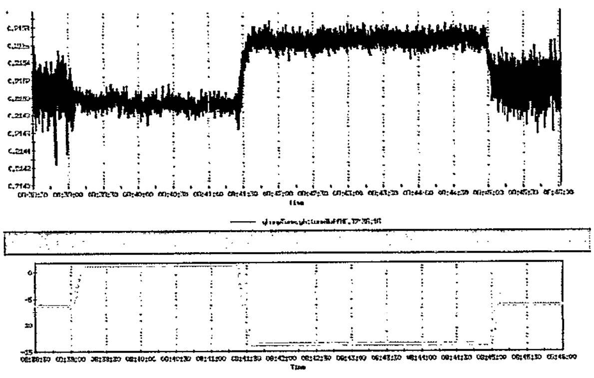

Figure 6. Tune shift vs. bump amplitude after octupole correction.

The residual linear tune shift from the sextupole was then operationally corrected with the local sextupoles. The right half of Figure 7 shows the cancellation of tune shift in IR8 after correction.

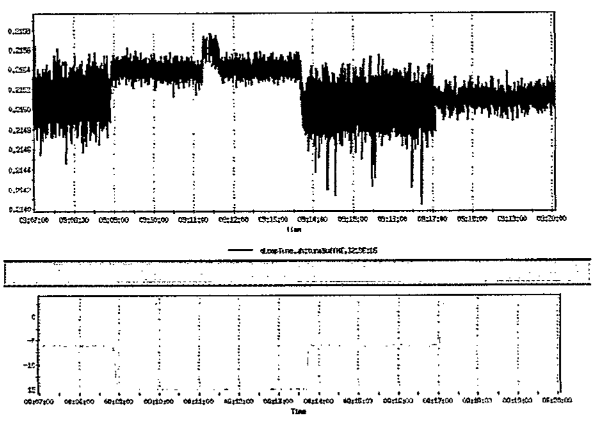

Figure 7. Tune shift during and after sextupole correction.

Notice in Figure 6 and 7 a variation in the resolution of the PLL tune data. The primary factor influencing PLL resolution is PLL loop gain. Included in the PLL loop gain is the beam transfer function, so variations in resolution then grow out of either changes in electronic settings, or changes in beam properties. The PLL resolution can vary by about four orders of magnitude, from about 10^{-2} to 10^{-6} units of fractional betatron tune. Larger loop gains and consequently poorer resolution are typically used for tune tracking during acceleration ramps, and smaller loop gains for beam studies where changes are more controlled and gradual and the bandwidth requirement is relaxed.

Table 3 summarizes the results of the local IR correction for the horizontal tune.. Table 4 lists the final settings for the correctors in IR8 (β^*= 3m).

Table 3. Tune shift in IP7 before and after IR correction.

Configuration IP7	ΔQ_H bump +12mm	ΔQ_H Bump −12mm
No correction	-0.0007	+0.0003
octupole	-0.0005	+0.0005
Octupole+Sextupole	0.000	0.000

Table 4 Final corrector strengths in IR8.

corrector	Strength (*kL*)
yi7-oct3	0.1
yi7-oct2	0.2
yo8-oct2	-0.1
yo8-oct3	0.0
yi7-sx3	-0.00025
yo8-sx3	-0.00225

4. PLANS FOR RUN 2003

Plans are in place to find and compensate the source of the gradient errors in the IR triplets, as we have no normal quadrupole correctors in the IR packages. Triplet roll errors are being measured at selected IR's and will be possibly corrected. Developments in the PLL system are planned for 2003 that will improve its reliability while maintaining the required resolution of ~10^{-5} for the IR bump measurements.

The plan for non-linear IR measurements and correction for run 2003 is the following. First, we will use the offline RHIC model to compare the experimental data with simulation predictions (machine with measured magnet and alignment errors). Experimental activity during 2003 will focus on completing the non-linear corrections in IR8, and possibly establishing a correlation with resonances in tune space, beam losses and lifetime.

5. REFERENCES

[1] J-P. Koutchouk, F. Pilat, V. Ptitsyn, "*Beam-based measurements of field multipoles in the RHIC low beta insertions and extrapolation of the method to the LHC*", PAC 2001

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[3] J. Cardona, S. Peggs, F.Pilat, V. Ptitsyn, T. Satogata, EPAC 2002, MOPLE060